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Distribution and extirpation of pigs in Pacific Islands: a case study from Palau

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ABSTRACT

*Neolithic arrival in the Pacific involved, as in other parts of the world, the translocation of domesticated plants and animals by pottery-making cultures in prehistory. Globally uncommon, though, was the abandonment of pottery on some islands and the extirpation of the pig (*Sus scrofa/verrucosus*) and dog (*Canis familiaris*) – the two largest mammalian quadrupeds introduced to Oceania – from the subsistence and cultural systems. This paper examines the extirpation of pigs from the Palau Islands as a case study to understand why an important domesticate has such an uneven prehistoric distribution. When suids are fed agricultural produce required to sustain the human population, it has been proposed that competition and extirpation will result, especially on small islands with limited arable land. However, pigs are considered problem animals in many environments because of the damage they cause to horticultural production, particularly the effects of free-range pigs on gardens and plantations. It is suggested that extirpation and low-level animal keeping are a response to the threat that pigs pose to plant food yields and social relations.*

Keywords: domestication, pig, Pacific, extirpation, agriculture.

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The loss of domesticated animals in Pacific prehistory is a perplexing phenomenon, because pigs and other commensals were significantly involved in the ethnographically observed economic, social and ritual systems of many oceanic societies (Ellis 1833; Harrisson 1937; Rappaport 1967). Island size has been related to extinction/extirpation of pigs when the size of the human population reaches a level at which there is competition between pigs and people for staple foods (Bay-Petersen 1983). Kirch *et al*. (2000) noted that trophic competition – the loss of calorific energy to large herds of pigs fed on agricultural crops – increased the likelihood of pig elimination on small relatively isolated islands (overnight sailing or greater to nearest island) with a high human population density (>200 persons per km^2 of arable land), intensive forms of agriculture and endemic warfare. Statistical testing of geographical variables by Giovas (2006) supported the view that island/archipelago size is critical to pig survival using the species–area relationship in biogeography, in which the smaller the landmass, the more vulnerable are its biota to extinction.

The central tenet of the trophic competition hypothesis is that as pig herds grow larger, they are fed increasing amounts of garden products required to sustain the human population. Under conditions of high resource stress and competition, the subsistence return from pigs on small islands is economically unsustainable, leading to the attrition and extirpation of pigs despite the high cultural value of suids. However, in many islands and environments pigs are reckoned to be problematic animals because of the damage they cause to gardens and social relations, rather than for the amount of produce they require to be fed (Heise-Pavlov & Heise-Pavlov 2003; Hide 2003: 160-161; Hughes 1970: 276; Sillitoe 1981). Rappaport's (1967) seminal study of pig keeping by the Tsembaga people of New Guinea suggested that without periodic slaughtering the pig population would grow quickly and cause serious damage to food crops. Historical and traditional records of pig–human interaction in Oceania similarly highlight the threat that pigs constitute to garden productivity (Dumont d'Urville 1987: 199; Ellis 1833: 67; Robertson 1973: 72). It follows that variability in the prehistoric record of pigs in the Pacific, particularly the absence/extirpation of suids on islands, is the result of strategies aimed, at least in part, at controlling the negative impact of pigs on horticultural yields and social relations.

In this paper, we examine the absence/extirpation of pigs on Pacific Islands by establishing, first, the prehistoric loss of pigs in the Palau Islands (Western Micronesia) in the second millennium AD by AMS dating of archaeological pig bone. Palau is an important case, as Rieth (2011) has suggested that trophic competition and

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archipelago size do not fully explain the extirpation of pigs, due to its size (415 km^2), low population density (75 people per km^2) and abundant marine resources. Second, we consider the chronological record of pig keeping on Pacific Islands. For example, were pigs absent during the colonisation phase, did they become extinct later in prehistory or were they extirpated in the late prehistoric/early historical era after centuries of domestication? The aim is to propose a broader range of explanations for the patchy geographical and temporal distribution of the pig in the Pacific.

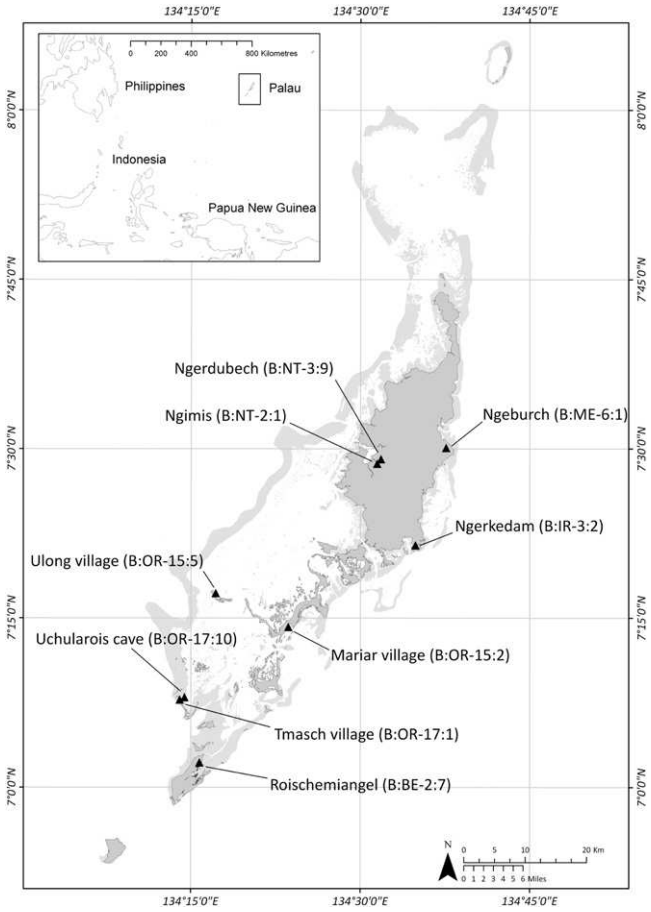
REVIEW OF *SUS* REMAINS FROM PALAU

The Palau archipelago (7°28′N, 134°34′E) consists of more than 350 tropical islands within the boundaries of the Indo-Pacific Warm Pool (Gagan *et al*. 2004). The largest landmass is the volcanic island of Babeldaob (333 km^2), which is separated from numerous small limestone islands in the Southern Lagoon known colloquially as the "Rock Islands", and the larger reef platform islands of Peleliu and Angaur. Palau has been inhabited for at least 3000 years (Clark *et al*. 2006), and the archaeological sequence, traditional history, geology and geography have been reviewed recently by several researchers (Fitzpatrick 2003; Liston & Miko 2012; Masse *et al*. 2006; Snyder *et al*. 2012). In summary, the oldest sites occur on limestone islands in the south of Palau, where carbonate sediments preserve cultural deposits, in contrast to the acidic soils of Babeldaob. Substantial earthworks were constructed on inland hills and ridges in 450 BC–AD 750, after which they were abandoned. Around AD 800–900, permanent settlements termed "stonework" villages were established on Rock Islands in the Southern Lagoon, but were abandoned around AD 1450, possibly due to increasing aridity (Clark & Reepmeyer 2012). On Babeldaob and other islands, coastal stonework/traditional villages based on pond field cultivation were inhabited into the historical era (Wickler *et al*. 2005).

Pigs were not seen in AD 1783 when the shipwrecked crew of the East India Packet *Antelope* camped on Ulong Island, nor were they seen on visits by the crew to other parts of Palau such as Babeldaob, Koror and Peleliu. Pig remains were introduced to Palau by the crew of the *Antelope* from preserved hams taken on board in China, but pig meat was not an item exchanged with Palauans in AD 1783 (Clark & de Biran 2010). It was not until 1791 that Captain McCluer introduced pigs to Palau – "four sows with young and a boar pig" (Lévesque 2000: 601) – and the animals were widespread in the archipelago by 1798 (Masse *et al*. 2006: 120).

Pig bone is recorded in southern Palau from five locations in contexts potentially of prehistoric age: Roischemiangel (B:BE-2:7) on Peleliu Island, Uchularois Cave (B:OR-17:10) and Tmasch village (B:OR-17:1) in the Ngemelis Group, Ulong village on Ulong Island (B:OR-15:5) and Mariar village (B:OR-15:2) on Ngeruktabel Island (Figure 1). On the main island of

Figure 1. Inset: the location of the Palau Islands in Western Micronesia. Main map: the Palau Archipelago (Southwest Islands not shown) and archaeological village sites where pig bone has been recovered.



Babeldaob, pig bone has been found at four stonework villages: Ngmis (B:NT-2:1), Ngerkedam (B:IR-3:2), Ngerdubech (B:NT-3:9) and Ngeburch (B:ME-6:1). Masse *et al*. (2006) consider pig remains from dated contexts in Uchularois Cave and Tmasch village in the Ngemelis Group show that *Sus* was present in Palau at AD 650 and survived in the Rock Islands until village abandonment by AD 1450. At the other archaeological sites, a review of excavated remains suggests that the association of pig bone with prehistoric deposits is problematic.

The Roischemiangel site is dated to AD 1150–1450, but most of the excavated pig bone found in Unit B occurred in upper levels (Levels 1–3, NISP = 4), with a single pig bone in Level 11. Glass, metal and other historical debris was found in nearly every excavation level and was concentrated in the upper 4–5 levels containing most of the pig bone (Beardsley 1996: 47), suggesting that pig remains, including the single bone from Level 11, could date to the historical period. At Mariar village on Ngeruktabel, a probable pig bone was recovered from EU-6 (0–10 cm), but the identification has not been confirmed (Smith 1981) and the near-surface context

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suggests it may postdate village abandonment. Excavations on Ulong Island by Osborne (1979: 66) recorded small quantities of pig bone in the Wall test unit from the base of Stratum II and top of Stratum III (~40–60 cm below surface), but excavation was by shovel and an association with abandoned village remains could not be confirmed.

At Ngeburch village, pig bone (NISP = 3) was found in the EU-42S 10E excavation, where historical artefacts were found to 20 cm depth, and at Ngerkedam village a fragment of "?pig mandible" was recovered from EU-24N 11W at 25–50 cm below surface (Smith 1981; Masse *et al*. 1982: 100-132; Masse 1989: 342-343); no radiocarbon dates were obtained from either excavation, and as both villages were occupied into the nineteenth century, the pig remains from them may belong to historical-era occupation. Similarly, at the Ngerdubech village site, pig bone (NISP = 2) occurred in a midden deposit (Fea. 81) likely to be of late prehistoric/early historical age (Liston 2011: 210-211).

At Ngmis village, pig remains were found in TP.4 (NISP = 1) and TP.2. At TP.4, the entire stratigraphic sequence was found to be disturbed (Wickler *et al*. 2005: 266). A larger assemblage of pig bone from TP.2 (NISP = 20) was concentrated in Layers Ia and Ib (0–30 cm depth), with the well-preserved condition of shell midden in acidic sediments indicating a late prehistoric or early historical midden age. A single fragment of pig cranium found in Layer II of TP.2 was tentatively dated by a mixed charcoal sample to 530 ± 80 BP (Beta-100011, AD 1310–1450). As pig cranial and mandibular fragments occur in the overlying Ia and Ib layers and downward movement of the cranial fragment in the sloping deposit cannot be ruled out, the Ngemis pig remains are also potentially of historical age.

To summarise, there are nine archaeological sites in Palau where pig bone has been reported, but only two sites in the Ngemelis Group are of definite prehistoric age with associated radiocarbon dates, indicating that *Sus* was present at Tmasch AD 1290–1450 and at Uchularois cave at AD 650–1450 (Masse *et al*. 2006). Elsewhere, particularly on Babeldaob and Peleliu, pig remains are not clearly associated with prehistoric deposits and may result from the historical introduction and rapid spread of pigs. The chronology of *Sus* in Palau is poorly resolved, and the attribution of East Asian haplotypes to prehistoric Palauan pigs (Larson *et al*. 2007) from the analysis of pig remains of potentially historical age from Ngmis village (TP.2, Level Ib) needs to be confirmed by genetic results on pig bone of known prehistoric age.

Direct dating of pig remains was undertaken to resolve uncertainty about the prehistoric status of *Sus* in Palau. Small amounts of pig bone were found in recent excavations at the Ulong village site (Clark *et al*. 2006) and pig was identified in a subset of the Uchularois cave fauna (Masse 1989) held by Te Papa Tongarewa Museum of New Zealand (Registration number AR000004).

ULONG ISLAND

Pig bone was identified in small quantities in the Unit 4 and Unit 5 excavations on Ulong Island (Supporting Table S1), with excavation details and radiocarbon dates reported in Clark *et al*. (2006), Ono and Clark (2010) and Petchey and Clark (2010). Most pig remains were found at the base of the cultural deposit (40–60 cm depth), associated with the establishment of a permanent village on Ulong Island around AD 900, with abandonment by AD 1450 (Clark & Reepmeyer 2012). Villages in the Rock Islands are defined by stone architecture (defensive walls, platforms and terraces) and midden debris containing ceramics, fish bone and marine shellfish (Masse 1989). A deciduous *Sus* tooth dP^4 and a permanent $M^{1/2}$ tooth displaying little attrition were found below the stonework village deposit, at 80–90 cm and 100–110 cm depth, respectively. A recent review of pig remains from Melanesia previously thought to date older than BC 1000 demonstrates that pig bones and teeth of late prehistoric age, like most small archaeological remains, can be introduced to older deposits (O'Connor *et al*. 2011). Displacement of the two pig teeth from the stonework village layer (40–60 cm) appears likely at Ulong, where there is 2.4 m of cultural deposit and land crab burrows, pits and postholes have the potential to disturb the stratigraphy, especially in beach sediments below the village deposit. The Ulong *Sus* remains include a deciduous tooth, elements with unfused bone ends and a maxillary molar that typically erupts prior to adulthood with no tooth wear (Hongo & Meadow 1998: table 3), indicating at least 1–2 pigs in the juvenile–subadult range. Pig bone from earlier excavations had identified fragments of a mandible from "a heavily built short faced pig", and bones from an adult pig showing that juveniles/subadults and adult pigs were present on Ulong (Osborne 1979: 66). A pig bone from the AD 1783 *Antelope* camp on Ulong Island was also dated to see whether accurate age results on *Sus* bone could be obtained.

UCHULAROIS ISLAND

Excavations of ~4 m^2 in Uchularois Cave by Masse (1989) recovered an assemblage of pig bones totalling 110 identified specimens (Supporting Table S1) from a deep midden deposit dominated by the remains of fish and shellfish (Carucci 1992; Masse 1989; Masse *et al*. 2006). Most pig remains were between 40 cm and 100 cm depth, with a small number found towards the base of the deepest unit (North ext.) and on the surface of EU-1. Radiocarbon dates from Uchularois Cave have been recently revised and suggest that midden deposition began at AD 900, with site abandonment by AD 1450 (Clark & Reepmeyer 2012). The pig bone was analysed by Smith (1981), who identified an MNI of five pigs based on a threefold stratigraphic division of the deposit (0–40 cm, 40–100 cm and 120–175 cm). The pig assemblage from Uchularois Cave could not be located except for a subset of bone held

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by Te Papa Tongarewa Museum of New Zealand from which AMS dating samples were selected (Supporting Table S1). The small number of elements in the 0–40 cm and 120–175 cm excavation levels is probably the result of disturbance, as two ^{14}C results on pig bone from below 120 cm depth gave age results similar to those of samples from the 40–100 cm levels containing most of the pig bone (see below). Combining all of the pig bone from Uchularois Cave in a single assemblage gives a MNI of 1–2 juvenile/subadults and one adult based on element size, a high proportion of deciduous teeth ($n = 14$) and presence of an M3 that in at least two individuals had not erupted or experienced visible tooth wear at the time of death ($n = 5$).

AMS DATING

All samples were prepared at the Waikato AMS radiocarbon facility following bone ultrafiltration methodologies outlined in Bronk Ramsey *et al*. (2004) and Petchey *et al*. (2011). Graphite targets were processed by the Waikato Radiocarbon Dating Laboratory in New Zealand, by the reduction of CO_2 with H_2 in a reaction catalysed by iron powder at a temperature of ~550°C. Stable C and N isotope measurements used for dietary reconstruction and quality control were measured at the Isotope Ratio Mass Spectrometry Unit, Otago University on a Europa Hydra coupled to a Carlo Erba NC 2500.

Ultrafiltered gelatin was assessed for purity prior to analysis using standard % gelatin yield, %N, %C and C:N quality assurance parameters (Table 1). Most well-preserved archaeological bone protein ranges between 11 and 16% N, with an average of 35% C and a C:N ratio range of 3.1–3.5 (Ambrose & Norr 1993: 403; van Klinken 1999). Values that fall outside this C:N range should be evaluated further. The amount of extractable protein (% gelatin yield) was also used as a guide to the reliability of the results, with any sample yielding < 0.5% of the starting weight of bone powder treated as suspect (Table 1). Bone belonging to Wk-30428 produced a low yield of 0.3%, but stable isotope quality control data indicated that the radiocarbon result is reliable.

Isotopic evaluation

$\delta^{13}C$ and/or $\delta^{15}N$ isotopic values from bone protein are regularly used as quantitative measures of different dietary protein sources for humans and animals (Field *et al*. 2009; Richards *et al*. 2009; Valentin *et al*. 2010). Stable carbon isotopes used for dietary correcting radiocarbon dates (Table 2) are assumed to have a linear relationship between marine and terrestrial food sources. Stable nitrogen isotopes indicate the tropic level of an organism and have been used to determine the amounts of animal versus plant protein (Schoeninger & DeNiro 1984). Although considerable uncertainty still exists with assigning precise dietary make-up, information of this type is vital to distinguish marine from terrestrial carbon input – radiocarbon reservoirs that differ on average by 400 years (Stuiver *et al*. 1986) – and provide reliable calendar ages on these remains (e.g. Beavan-Athfield *et al*. 2008; Petchey & Green 2005; Petchey *et al*. 2011).

Environmental conditions also create differences in $\delta^{13}C$ values (van Klinken 1999) and it is therefore necessary to establish baseline data for the region under study. Isotopic data for pig remains from Palau are limited, but information from archaeological sites across the Pacific indicate that pig with a 100% terrestrial (C3) diet would have a $\delta^{13}C$ of $-20 \pm 1‰$ (Beavan-Athfield *et al*. 2008; Field *et al*. 2009: table 3; Jones & Quinn 2009; Valentin *et al*. 2010: table 3), while pigs subsisting on an 95% marine diet have a $\delta^{13}C$ value of around $-10 \pm 1‰$ (Richards *et al*. 2009: 36). In these datasets, $\delta^{15}N$ values for pigs eating only terrestrial protein fall between 7 and 10.3‰, while those assumed to have a predominantly marine diet return values that fall between 14.4 and 18.3‰. Calculating a suitable dietary correction for radiocarbon dates of pig bone from the Pacific is further complicated because of a possible combination of marine, reef and freshwater foods, as well as C-3 and C-4 plants (e.g. grasses, seagrass, seaweeds [red algae]) and freshwater sources that confuse $\delta^{13}C$ and $\delta^{15}N$ isotopic signatures (Ambrose *et al*. 1997). Since pigs are generally considered to have an opportunistic and omnivorous diet, all possibilities need to be considered.

Because of these limitations, we have made a number of assumptions on the basis of archaeological and

Table 1. AMS bone quality control data.

Lab. no.	Element	Age	Gelatin yield (%)	%N	%C	C:N
Wk-29864	Right, tibia – midshaft	Juvenile/subadult	2.75	15.3	44.7	3.4
Wk-30710	Right, humerus – midshaft	Juvenile/subadult	0.72	15.6	44.2	3.3
Wk-30711	Left, metacarpal	Juvenile/subadult	1.05	15.7	44.6	3.3
Wk-30428	Tooth – M^1/M^2	Juvenile/subadult	0.30	15.0	42.7	3.3
Wk-29869	Right, mandible – ramus	Juvenile/subadult	1.05	14.9	44.2	3.5
Wk-29868	Vertebra – fragment	Juvenile/subadult	1.38	15.3	44.0	3.4
Wk-29867	Rib – midshaft	Juvenile/subadult	1.28	15.0	43.8	3.4
Wk-29866	Rib – shaft fragment	?Juvenile/subadult	2.12	15.3	44.2	3.4
Wk-29865	Left, mandible – symphasis	Juvenile/subadult	0.57	14.7	43.1	3.4

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Table 2. Radiocarbon and isotope data.

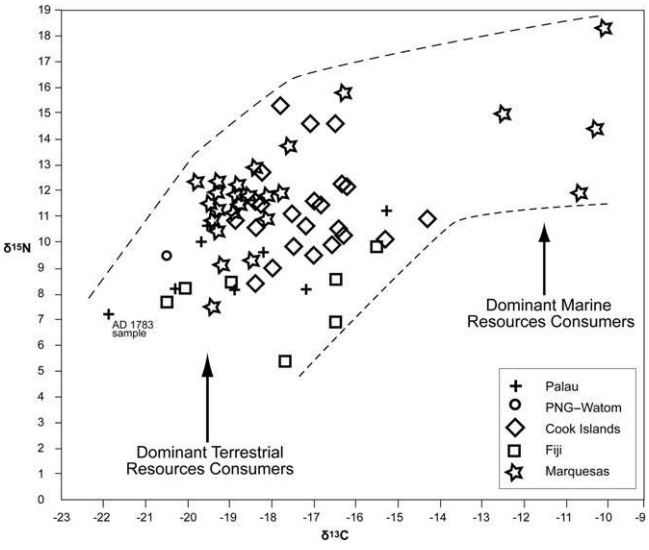
Context	Lab. n0.	CRA†	Gelatin isotopes‡		%MarineC	Years AD (68.4% prob)
			$\delta^{13}C$	$\delta^{15}N$		
Ulong: Englishman's Beach, TP.3: 60–70 cm	Wk-29864	161 ± 28	–21.9	7.2	na§	1670–1690, 1730–1780, 1800–1810, 1925–1945
Ulong: Unit 5: 40–50 cm	Wk-30710	987 ± 25	–20.3	8.2	2.3	1030–1155
Ulong: Unit 5: 40–50 cm	Wk-30711	1077 ± 25	–18.9	8.2	15.7	985–1060, 1080–1150
Ulong: Unit 4: 100–110 cm	Wk-30428	1257 ± 26	–16.5	–	38.0	725–850, 855–1030
Uchularois: North ext.: 50–60 cm	Wk-29869	1245 ± 31	–18.2	9.6	21.9	805–975
Uchularois: North ext.: 70–80 cm	Wk-29868	1187 ± 29	–19.5	10.7	9.5	868–1010
Uchularois: North ext.: 90–100 cm	Wk-29867	1270 ± 29	–15.3	11.2	49.5	857–1065, 1095–1110
Uchularois: North ext.: 130–160 cm	Wk-29866	1183 ± 30	–19.7	10.0	7.6	870–990
Uchularois: North ext.: 163–175 cm	Wk-29865	1270 ± 29	–17.2	8.2	31.4	810–990

†Conventional radiocarbon age as defined by Stuiver and Polach (1977), with $\delta^{13}C$ measured directly on the prepared graphite (not reported).
‡Isotopes measured on ultrafiltered gelatin. $\delta^{13}C$ values were measured relative to the VPDB standard and have errors of ± 0.2‰. $\delta^{15}N$ values were measured relative to the AIR standard and have errors of ± 0.3‰. $\delta^{13}C$ for Wk-30428 was measured on CO_2 generated during AMS combustion.
§The pig bone for Wk-29864 was obtained from the European camp associated with the AD 1783 shipwreck of the *Antelope* (Clark & de Biran 2010).

economic evidence at Ulong and Uchularois. First, C-4 plants are a minor component of the sand plain and limestone flora of the Rock Islands (Kitalong 2008). Economically important plants such as atoll taro (*Cyrtosperma chamissonis*), coconut (*Cocos nucifera*), banana (*Musa* sp.) and Malay apple (*Syzygium malaccensis*) that grow well in the Rock Islands are C-3 (Allen & Craig 2009; Beavan-Athfield *et al*. 2008; Leach *et al*. 2001; West 2007). This argument remains if the pigs were raised off island (e.g. Babeldaob), where despite a greater potential supply of C-4 plants, the main economic plants were C-3. Other sources of C-4 plants such as seagrass beds are minimal in the region around Ulong and Uchularois (Colin 2009).

We have assumed that a diet devoid of C-4 plants and freshwater foods would also be limited on Ulong and Uchularois, as there is no standing water; in prehistory, people tapped the freshwater aquifer to obtain a tidal supply of fresh water. Our interpretation of the Palau pig isotope values (Table 1 and Figure 2) points to domesticated pigs being fed a diet that is composed predominantly of terrestrial C-3 foods with occasional marine food scraps. Marine foods were important to stonework village subsistence from high concentrations of finfish and marine shell remains in village middens (Masse 1989; Ono & Clark 2010) and the relatively small amount of horticultural land available in the Rock Islands. Because marine protein is preferentially routed to the bone collagen, the supplementation of even small amounts of marine food (probably herbivorous and omnivorous fish) into the pig diet causes the elevated and varied %marineC signature (Table 2) used for ^{14}C calibration purposes. In Figure 2, the increased scatter in the isotope data from the Marquesas compared to PNG-Watom, Cook Islands, Fiji and Palau likely reflects greater amounts and diversity of marine food being fed to some pigs (West 2007).

Figure 2. A comparison of Palau pig $\delta^{13}C$ and $\delta^{15}N$ isotopic values with those of prehistoric pigs in the Cook Islands (Allen & Craig 2009; Craig 2009), Marquesas (Richards *et al*. 2009; West 2007), PNG–Watom (Beavan-Athfield *et al*. 2008) and Fiji (Field *et al*. 2009; Jones & Quinn 2009).



Calibration

The pig bone determinations (Table 2) were calibrated using the mixed calibration option in OxCal v4.1 with curve resolution set at 5 (Bronk Ramsey 2012). This program calculates the calibration curve valid for a given fraction of marine carbon (%marineC) by linear interpolation between the terrestrial calibration curve (IntCal09) and the marine curve of Reimer *et al*. (2009). The %marineC values used were calculated by linear interpolation using the single isotope option in the

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program ISOERROR 1.04 (Phillips & Gregg 2001). We selected $\delta^{13}C$ endpoint values of −20.5‰ for purely terrestrial (C3) diets and −10‰ for a purely marine diet. An error of ± 20% has been applied to these values, as recommended by Petchey *et al*. (2011).

The calibrated age result on pig bone from the historical AD 1783 site on Ulong has a wide age spread, with the most likely (35% probability) AD 1730–1781 range close to the period of site use. Prehistoric pig on Ulong Island dates to ~AD 800–1200 and a similar range is likely at Uchularois cave (~AD 800–1100), where there is little variability in pig bone ages from basal and upper layers. The pig remains excavated by Masse (1989) at Tmasch are bracketed by marine shell determinations of AD 1000–1300 (Clark & Reepmeyer 2012).

INTRODUCTION OF PIGS TO PALAU

Direct dating of pig bone from Palau indicates that *Sus* was extirpated from Rock Island villages by AD 1300 prior to their abandonment around AD 1450, but the results do not necessarily disclose when pig first arrived in Palau, nor if the animal survived longer on Babeldaob and the reef platform islands of Angaur and Peleliu (Masse *et al*. 2006; Rieth 2011). No pig remains of definitive prehistoric age are known from Yap and the Marianas Islands (Clark 2005; Intoh 1986; Intoh & Shigehara 2004). On the small raised island of Fais, 750 km east of Palau, pig may date as early as AD 220–450, although the majority of domesticated animal bones are from cultural phases dated to AD 600–1300. Elsewhere, pigs were introduced during the Lapita era on Taumako, the Bismarck Archipelago and Vanuatu (Bedford 2006: 258; Leach & Davidson 2008: 296; Summerhayes 2010) and were probably widely distributed in New Guinea 2500–2000 years ago (McNiven *et al*. 2012: 138). Current distributional evidence suggests, then, that Palauan *Sus* could have been introduced directly from several sources, including Island South-East Asia–New Guinea suids brought to the Pacific during the Lapita era, or could potentially be East Asian *Sus* from the Ryuku Island region (Minagawa *et al*. 2005; Watanobe *et al*. 2002).

We now develop a framework for understanding the distribution and extirpation of pigs by examining the chronological absence/extirpation of *Sus* from the archaeological and historical records of islands in the Pacific and the North Atlantic where pigs were also extirpated.

Absence in the colonisation era

The absence of prehistoric pig in colonisation deposits is difficult to confirm on several island groups due to poor preservation conditions and a problematic association of pig remains with early cultural deposits (e.g. Anderson 2009; O'Connor *et al*. 2011; Rieth 2011). In Western Micronesia, pig was not introduced to the Marianas at 1400 BC, nor does it occur in the oldest deposits yet reported from Palau (1100 BC) and Yap (Intoh 1986). New Caledonia does not appear to have pig in its Lapita deposits and the arrival of pig with the earliest Lapita groups is unresolved for Fiji (Clark & Anderson 2009; Irwin *et al*. 2011), Tonga (Anderson 2009; Burley 1998) and Samoa (Smith 1999: 270–288; cf. Addison & Matisoo-Smith 2010: 5). Claims for the presence of pig in Lapita sites in Fiji and Tonga are in several instances based on incorrect identifications. At the Yanuca site (VL 16/81), a bone identified as a pig femur is a turtle/tortoise humerus (Worthy & Clark 2009: 254); at Bourewa, a pig bone estimated to date to 900 BC is, in fact, a human cervical vertebra (http://WikiEducator.org/images/2/2a/Pig_bone_Bourewa_excavations.JPG); and in Tonga, examination by Clark and Hawkins of bone from the To.1 shell midden showed that turtle and human remains have been misidentified as pig (Poulsen 1987: 243-244). It is plausible, therefore, that pig may have been a late Lapita or post-Lapita introduction to Fiji–West Polynesia, as Best (1984: 544) hypothesised. It is striking that all of these island groups, with the exception of New Caledonia, required a lengthy ocean crossing in excess of 800 km in the period 1400–900 BC. A voyage of 850 km was needed to transport pigs from Vanuatu to Fiji–West Polynesia, and Palau–Yap–Marianas is separated by 800–2200 km of ocean from potential source populations in Island South-East Asia and New Guinea.

In East Polynesia, prehistoric pig is absent on Rapa Nui and New Zealand–Aotearoa, and voyages of more than 2000 km were required to settle these landmasses, which were colonised AD 1200 (Anderson 2000). It is unclear how long Pacific pigs could survive on long canoe voyages, particularly those in temperate latitudes. Mortality rates were potentially high, as suggested by the death of Pacific pigs collected on Raiatea (16°50′S) in 1769 by James Cook (1893: 199), which began to die on the way to New Zealand at 24°S on August 15: "As we advanced to the Southward into Cold weather, and a troubled Sea, the Hogs we got at Ulietea began to die apace. They cannot endure the least cold, nor will they hardly eat anything but vegetables, so that they are not at all to be depended upon at Sea."

Difficulty in transporting sufficient pigs to establish viable breeding populations is implicated in the absence of pigs from the colonisation phase deposits of several moderate-to-large island groups (Table 3), although the antiquity of *Sus* in Palau–Yap and Fiji–West Polynesia clearly requires additional chronometric research. The exception is the Hawaiian Islands, where pigs were introduced through canoe voyages 2000–3000 km in length. Hawaii is within the tropics, however, while New Zealand (34–47°S) and Rapa Nui (27°S) are subtropical/mid-latitude landmasses, suggesting that pig survival on long canoe voyages was dependent on temperature gradients, sea conditions and the presence of sufficient fodder and fresh water to support animals on long sea passages.

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Table 3. Examples of pig presence/absence mentioned in the text in relation to island geography.

Location	Presence/ absence†	Area (km^2)	Geology	Climate zone	Isolation‡
Mariana Islands	1	1018	Island arc	Tropical	High
Yap	1	105	Island arc	Equatorial	High
Palau	1	459	Island arc	Equatorial	High
New Caledonia	2	18580	Continental	Tropical	Moderate
Fiji	1	18270	Continental/island arc	Tropical	High
Tonga	1	748	Island arc	Tropical	High
Samoa	1	2831	Volcanic	Tropical	High
Rapa Nui	1	164	Volcanic	Subtropical	High
New Zealand	1	268700	Continental	Subtropical/mid-latitude	High
Palau–Ulong	3	1.2	Raised limestone	Equatorial	High
Palau–Ngemelis	3	1.4	Raised limestone	Equatorial	High
Solomons–Rennell	3	660	Raised limestone	Tropical	Moderate
Solomons–Bellona	3	18	Raised limestone	Tropical	Moderate
Solomons–Tikopia	4	4.6	Volcanic	Tropical	Moderate
Gambier–Pitcairn	3	4.2	Volcanic	Tropical	High
Gambier–Henderson	3	37	Raised limestone	Tropical	High
Gambier–Mangareva	3/4	18	Volcanic	Tropical	High
Cooks–Mangaia	4	52	Volcanic/raised limestone	Tropical	Moderate
Cooks–Aitutaki	4	18	Volcanic/raised limestone	Tropical	Moderate

†Presence/absence: 1, failure to establish pigs during the colonisation era; 2, cultural decision not to introduce pigs; 3, introduction followed by extirpation in prehistory; 4, low-level husbandry, maintenance of a small local breeding group and/or importation of pigs.
‡Isolation: high, distance to landmass with pigs exceeds 500 km; moderate, distance to landmass with pigs is 150–250 km.

Extirpation in the prehistoric period

There are surprisingly few islands where the extirpation of pig dates unambiguously to the prehistoric era. In East Polynesia, pig bone occurs on Henderson Island and Pitcairn Island, both of which were abandoned by AD 1500–1600 (Gathercole 1964; Weisler 1994). In the Solomon Islands, pig bone was found with plain pottery, including a carinated bowl, at the Sikumango (Be.53) site on Bellona Island (Poulsen 1972), and on nearby Rennell Island several pig teeth were found at the base of the LC-2 rock shelter (Chikamori & Takasugi (1985: 107): both sites are tentatively dated to AD 0, but it is not known when the islands were first colonised. The extirpation of pigs in the Rock Islands of Palau by AD 1300 is another example, but there is no obvious geographical variable that links these cases. Bellona (18 km^2), Rennell (660 km^2) and Henderson (37 km^2) are carbonate islands, while Pitcairn (4.2 km^2) is volcanic and Palau (459 km^2) contains a mixture of volcanic, carbonate and volcanic–carbonate islands. Relative isolation differs markedly, with Rennell–Bellona 170 km from large islands in the Solomons. Henderson and Pitcairn are 500–700 km from Mangareva, and Palau is 800 km from landmasses where prehistoric pigs were present (Table 3).

One similarity is the loss of pigs on proximate islands in each area (Bellona–Rennell, Henderson–Pitcairn, Palau Rock Islands), which suggests that *Sus* had a peripheral role in the prehistoric economic, subsistence and social systems, and was extirpated when keeping of the animals impacted land management practices and horticultural productivity. When pig keeping on islands involves free-range foraging rather than sty-kept animals, there is potential for pigs to become problem animals because of their high reproductive rate and the damage they cause to crops, particularly when increasing amounts of free-range land is converted to garden.

In the North Atlantic, pigs were an important part of Landnam sites (AD 900–1100) in Greenland, Iceland and the Faroes, but did not survive as a major element of the domestic economy beyond the eleventh century AD, except in the Faroes, where they went extinct in the Middle Ages (Church *et al*. 2005; Dugmore *et al*. 2012). On Iceland, palaeoecological and zooarchaeological records show that pig keeping declined as local woodlands, which made free-range pig keeping inexpensive, were removed (Arge *et al*. 2009: 24). A shift in pig isotopes between the British Neolithic and the Iron Age is attributed to deforestation and increased agricultural use of the landscape in the Iron Age that led to closer management of the pig population (Hamilton *et al*. 2009). Historical accounts from Iceland and the Faroes make it clear that pigs were problem animals because they damaged gardens and fields and caused disputes (McGovern *et al*. 2007), as in the Pacific (Sillitoe 1981; West 2007: 94).

The effects of contemporary free-range and feral pigs on garden and plantation productivity is a common reason to change pig management systems (South Pacific Bureau for Economic Cooperation 1982: 5), as Phengsavanh and Stür (2006: 61–62) note for villages in Laos: "In areas where crop production has become more intensive . . . the amount of crop damage caused by free-range scavenging pigs has become a village issue . . . As the number of conflicts increased the village committee (or district

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government) saw no alternative but to issue a regulation banning free scavenging, either during the crop growing period or for the whole year. This has forced many households to start confining pigs in enclosures and pens." Thus, the prehistoric extirpation of pigs in several Pacific Islands may reflect the point at which the benefit of keeping free-range pigs was outweighed by the economic and social costs of feeding and managing pigs in landscapes increasingly dedicated to horticultural production, particularly as the amount of arable land for shifting cultivation grew, and intensified dryland, irrigated and arboriculture systems were developed (Kirch 1984).

Extirpation in the late prehistoric/early historic era

The archaeological record of pig suggests that it was extirpated on several islands in the late prehistoric/early historical era, notably Tikopia, Mangareva, Mangaia and Aitutaki. On three of these islands, pig was known, but had apparently been extirpated prior to European contact as a result of trophic competition between pigs and people (Kirch *et al*. 2000). Inspection of the voyaging literature suggests that pig, while very rare, actually survived on several of these islands into the historical period. Peter Dillon (1972: 134) and Dumont d'Urville (1987:199) visited Tikopia in 1827–1828 and recorded that pigs were extirpated because of the damage they caused to food crops, and that pigs were no longer raised. However, Dumont d'Urville (1987: 202) later noted that "I was reliably told that there were no more than two or three pigs on the whole island . . .", indicating that small numbers of pigs were occasionally raised or brought to the island. Mangaia did not have pigs in 1822 when London Missionary Society missionaries arrived, but it seems likely that *Sus* was present when Captain Cook visited on 29 May 1777. The day after arriving at Mangaia, Cook's journal (Rickman 1781: 81) mentions that the ship's boats attempted to find an anchorage, as fresh water was in short supply. During the unsuccessful search, Cook was told that there were no pigs or dogs on the island, although Mangaians had heard of both these animals. The journal of the marine John Ledyard (1783: 23) recorded, however, that during the search the boat crews received from Mangaians "Some hogs, some fruit, and some manufactures of the country. . ." (the accuracy of Ledyard's journal is discussed by Smith 2007), indicating that pig was probably extant in small numbers on Mangaia, as also suggested by two place names incorporating the Polynesian word for pig, *puaka* (Gill 1876: 15), and pigs were certainly present on Atiu.

Pigs are also suspected to have been extirpated prehistorically on Aitutaki (Craig 2009: 241-242; Tent & Geraghty 2012: 17-18), yet the historical record is ambiguous. When Captain Bligh (1792: 147) arrived on the island in April 1789, the status of pigs was unclear: "Notwithstanding they said that no hogs were on the island it was evident they had seen such animals; for they called them by the same name as is given to them at Otaheite. . .". During his second voyage to the Pacific, Bligh (1920: 132) again made a brief visit to Aitutaki in July 1792 and questioned the inhabitants about the presence of pigs, although again he did not go ashore: "It was understood they had no hogs on shore, but I suspect they meant to say that they were scarce . . .". The archaeological record of Mangareva initially suggested that pigs were extirpated by the fifteenth century AD, with subsequent work indicating that *Sus* was present into the latter part of the seventeenth century AD (Green & Weisler 2004; Hiroa 1938: 195). Mangareva was seen by the *Duff* in 1797, but a shore visit was not made until December 1825–January 1826, when it was found that the island had neither dogs nor hogs. However, the islanders apparently knew of pigs, as they used the word *boa*/Tahitian *pua'a* to describe European dogs (Beechey 1831: 154).

The absence/small number of pigs in the late prehistoric/early historical era (Table 3) suggests that the problems associated with pig keeping on Tikopia had been resolved by raising small numbers of pigs and/or by the occasional importation of pigs from neighbouring islands such as Vanikoro, which was visited by people from Tikopia. A few pigs on Mangaia and Aitutaki might similarly represent a small local population that was supplemented by imports of pigs from other parts of the Cook Islands. On Mangareva, pig may have gone extinct prior to the eighteenth century and replenishment would have been difficult given the distance from the Society Islands, and evidence that long-distance voyaging declined after AD 1500 (Green & Weisler 2004). The available data points to pig on these islands being a relatively rare high-status food/offering that was occasionally imported, with *Sus* having a minor role in the overall subsistence economy of the islands.

DISCUSSION

Although commensal animals were an important part of Neolithic lifeways, there are several instances around the world where introduction was followed by extirpation or very limited animal keeping. In Africa, the introduction and propagation of domestic animals such as cattle and pig was hampered by environmental conditions in Central and East Africa (Hassan 2000: 81; Marshall 2000; Van Neer 2000), domestic cattle went extinct a few centuries after introduction on Cyprus (Guilaine & Briois 2001: 40), and pig went extinct in several parts of the world, including some North Atlantic islands and islands near the Okinawa Island (West 2007: 60), in addition to islands in the Pacific such as Palau.

Precipitation levels have an important effect on pig keeping, with higher average rainfall during El Niño responsible for an increase in wild pig numbers in the Galapagos Islands (Campbell 1999) and drought causing losses, particularly among the domesticated 0–6 month age cohort on Niuatoputapu in Tonga (Kirch 1988: 33). The difficulty of keeping pigs on coral islands with restricted fresh water and terrestrial resources is evidenced by severe nutritional stress markers in prehistoric pig teeth from Fais

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(Kierdorf *et al*. 2009). The effect of climate on the absence of pigs in Palau (Masse *et al*. 2006) is the subject of current research, but climate change appears unlikely to have caused extirpation, as pigs seem to have disappeared in the Rock Islands by AD 1100–1300, prior to village abandonment around AD 1450–1500 (Clark & Reepmeyer 2012).

Pig keeping is subject to cultural prohibitions by Jews and Muslims (Hesse 1990), and on mainland Japan pig farming was interrupted for around a millennium because of Buddhist prohibitions and Shinto views about pigs (Watanobe *et al*. 2002). The absence of pigs in New Caledonia over 3000 years suggests that people did not want these animals and when Captain Cook attempted to introduce them he was told to take them away, which Tent and Geraghty (2012: 17) suggest was because people knew the damage that pigs caused to plantations. This is a common explanation for ambivalence towards pig keeping in the Pacific, with most complaints among the Highland Wola relating to pig damage to gardens and crops (Sillitoe 1981). The impossibility of growing unfenced root crops with free-ranging wild and domesticated pigs is noted on several Pacific islands (Green & Weisler 2004: 38; Walter 1998: 78) and is a reason for the exclusion of pigs in the Torres Strait Islands and Marshall Islands (Green & Weisler 2004; McNiven 2008: 457). Nonetheless, a failure to introduce pigs to several archipelagos, such as the Marianas and New Zealand, during the colonisation era probably reflects the limits of canoe transport with cultural prohibition, either due to the belief system or resulting from the deleterious effects of pigs on garden productivity, a plausible explanation, especially when the distance separating islands with pigs from those without pigs is within known voyaging zones (e.g. New Caledonia).

CONCLUSION

Pigs have a discontinuous distribution in the Pacific and, like other commensals, were subject to extinction after introduction from inbreeding, disease and poor environmental conditions, in addition to cultural decisions based on ideological, hygienic and economic circumstances. During the colonisation phase, pig dispersal and population establishment were most likely facilitated by free-range scavenging due to the relative abundance of forest/jungle forage in new landscapes. In the absence of predators, disease and low-fertility soils, pig numbers would grow at little cost to a colonising human population. Large numbers of pig remains in colonisation-era deposits need not indicate intensive husbandry and the maintenance of early pigs on agricultural foods, but instead reflect the presence of a free-range scavenging pig population under benign environmental conditions.

It is proposed that human population growth, deforestation and an increasing emphasis on crops to meet the bulk of community subsistence contributed to a decline in the wild resources available to pigs, and in some cases led to social conflict from pig damage to agricultural systems and lowered garden productivity. Free-range pig populations can be managed by reducing the total number, culling older animals that pose a greater threat to gardens, controlling pigs by tethering or confining them to a structure (slatted floor, earth enclosure or pen) and fencing gardens, all of which require people to contribute additional time, labour and food to support pig production. The problems posed by free-range pigs would have been unanticipated by colonising groups, and experienced by people living centuries later in heavily modified and often highly circumscribed landscapes increasingly dedicated to agricultural production. Low-level pig keeping – including the importation of animals in lieu of maintaining a breeding population – and extirpation should be considered predictable responses to a need to manage pigs more intensively, particularly with the expansion and intensification of horticulture in prehistory. Pigs were successfully incorporated into many Pacific Island economies, and were especially important in the stratified Polynesian chiefdoms of Tahiti, Tonga and Hawaii, but this should not mask the fact that pig keeping in prehistory included less intensive forms of husbandry. The above model has similarities to the trophic competition hypothesis in viewing population growth and agricultural intensification as contributing to pig extirpation, particularly on small islands, but differs from it in having extirpation most likely to occur when pig keeping transitions from a low-cost free-range system to forms of husbandry requiring greater management of pigs, crops and social relations.

There are few direct dates on domestic animal remains from the Pacific, in addition to frequent uncertainty over the provenance of commensal remains and accuracy of faunal identifications (Anderson 2009; Wickler 2004: 32). AMS dating of identified bone suggests that pigs were introduced to Palau's Rock Islands when permanent villages were established at ~AD 800–900 and were probably extirpated several centuries later. Consideration of the absence/extirpation of pigs on other islands suggests a link between the development of agricultural landscapes and the transformation of pig management systems, including in some instances the eradication of pigs from the social and economic landscape.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Table S1. Pig bone identifications from Uchularois cave and Ulong Island Unit 4 and Unit 5 (Clark *et al*. 2006). Teeth that could not be identified to the maxilla/mandible are identified by the absence of superscript/subscript.

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